The Use of Head Mounted Displays (HMDs) in High Angle Climbing:
Implications for the Application of Wearable Computers to Emergency Response Work

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Ehara taku toa, he takitahi, he toa takitini.

Tēnā rāwā atu koutou.

"I am turned into a sort of machine for observing facts and grinding out conclusions."

—Charles Darwin—

1. Abstract

As wearable computers become more ubiquitous in society and work environments, there are concerns that their use could be negatively impactful in some settings. Previous research indicates that mobile phone and wearable computer use can impair walking and driving performance, but as these technologies are adopted into hazardous work environments it is less clear what the impact will be. The current research investigated the effects that head mounted display use has on high angle climbing, a task representative of the extreme physical demands of some hazardous occupations (such as firefighting or search and rescue work). We explored the effect that introducing a secondary word reading and later recall task has on both climbing performance (holds per meter climbed and distance covered), and word reading and recall (dual-task effects). We found a decrease in both climbing performance and word recall under dual task conditions. Further, we examined participant climbing motion around word presentation and non-word presentation times during the climbing traverse. We found that participants slowed around word presentations, relative to periods without word presentation. Finally, we compared our results to those found in previous research using similar dual-tasking paradigms. These comparisons indicated that physical tasks may be more detrimental to word recall than seated tasks, and that visual stimuli might hinder climbing performance more than audible stimuli. This research has important theoretical implications for the dual-tasking paradigm, as well at important practical implications for emergency response operations and other hazardous working environments.

2. Introduction

2.1 Wearable Computers

Wearable computers are becoming more and more available to everyday users (Ngai, Chan, Cheung, & Lau, 2010). They can be conceived of as computers worn on the body, that are always on and available, and are aware of the user and their environment (Rhodes, 1997). These devices can provide the opportunity for intelligent assistance to users when they require it (Weiland, Zachary, & Stokes, 2000), with typical applications including physiological monitoring, and display of information with integrated control systems in clothing or other atypical places (Ngai et al., 2010). Some wearable computers have been developed with conventional PC interaction in mind (e.g. the WIMP: Windows, Icons, Menus, Pointing device paradigm; Baber, 2001). Previously, this focus on traditional interaction modes, akin to regular computer interaction, was common, with voice commands being the only "hands free" concession made (Weiland et al., 2000). Equally, it is entirely plausible that wearable computers employ their own interaction paradigm (such as head gestures, or eye movement interactions), leading to important ergonomic questions around user interaction with these devices (Baber, Knight, Haniff, & Cooper, 1999). Now with wearable headsets such as Google Glass (Google, n.d.), Recon Jet (Recon Instruments, 2015) or the Epson Moveiro (Epson America, Inc., 2010), the interaction is more on the side of novel touch gestures, analogous to touch screen smart phones. The utility of these interaction paradigms will be of concern in work environments, such as search and rescue, and firefighting, where the display of real time GPS and map information, as well as situational reports, could be useful.

With a solid understanding and application of the human factors around wearable computers, they could become effective tools. Thus, one might expect that wearable computers could improve things such as situational awareness, given that they can be incorporated into emergency responders' activities in ergonomic ways. Wearable computers are also tipped to capture the attention of people not otherwise drawn to technology (Ngai et al., 2010). Whether this is positive or problematic is debatable; using a wearable computer during the daily activity of driving diminishes driving performance (Sawyer, Finomore, Calvo, & Hancock, 2014). Because of the increase in application of wearable computers, particularly head mounted displays (HMDs) or head worn computers (HWCs), to everyday use and work contexts, it is important to consider the limitations of human processing and to ensure devices are suitable in, or adaptable to, these contexts (Mustonen, Berg, Kaistinen, Kawai, & Häkkinen, 2013).

2.1.1 HMDs

A Head Mounted Display (HMD) is a computer device worn on the head that displays information to a user, typically through a screen (Bretschneider, Brattke, & Rein, 2006). HMDs could be particularly useful in learning or adapting to novel situations. Wearable computers appear to facilitate collaborative work settings, engender improved performance, and can be useful in observational learning, which can lead to improved acquisition of skills (St-Onge et al., 2013). Using HMDs to get a first person perspective of an experienced surgeon at work could be invaluable to trainees (Schreinemacher, Graafland, & Schijven, 2014), however, HMD based observations may not substitute for in-person learning and observations. HMDs were initially developed for astronauts and pilots (Tomilin, 1999); they can be both monocular and binocular displays and are capable of presenting a wide range of information to a user. In monocular displays (such as Google glass) one eye has 'free sight' while the other can view the display, with a user usually being able to switch between focusing on the environment and display with relative ease, while the screen can be placed in various positions relative to the eye (Bretschneider et al., 2006).

With the development of Google Glass (Google, n.d.), and similar systems, HMDs are becoming increasingly available to consumers. They are expected to be incorporated into military, law enforcement, and search and rescue jobs in the future (Baber et al., 1999; Green & Helton, 2011) and are already being applied to fields such as surgery, engineering, entertainment and gaming (Bretschneider et al., 2006). The incorporation of HMDs into these environments leads to questions around the cognitive impact they will have, given that users would likely be doing more than one task at a time, or dual-tasking. Indeed, one of the benefits of HMDs is their ability to untether the user from a desktop; they are likely to be used in tasks where the person is physically active, not seated. Typically, wearable computers do expect users to complete both a primary real world task and a secondary wearable task (Witt, 2007). These concerns are especially germane considering that there is a large variety of optical systems (Bretschneider et al., 2006), and it is unclear how people interact with them in any number of contexts.

2.1.2 Applied Contexts

Within a more applied context, HMDs have the potential to improve firefighter safety and efficiency, with displays of maps with real time positional systems (GPS), biometric data, thermal imaging, or environmental status likely to improve safety and situational awareness (Bretschneider et al., 2006). For pilots, HMDs can be used to display infrared radiation images when viability is poor (Tomilin, 1999). The hands-free nature of HMDs make them well suited for these applications, and even though loading the body with extra weight could impact musculoskeletal mechanics (Baber et al., 1999), the light weight nature of this newer generation of HMDs and wearable computers should have minimal impact. For hazardous, high-risk or heavy-duty applied environments, however, a major increase in the robustness of HMDs would likely be required before use in these settings.

This is one of the major necessities of HMDs expressed by firefighters (Bretschneider et al., 2006).

Wearable computers could provide users with more information than is directly perceivable from the environment (Baber et al., 1999). This rapid easy access to information, enhanced environmental interaction and their small lightweight nature, make HMDs practical tools for many fields (Mustonen et al., 2013). A bonus of wearable computers is that they can turn everyday objects into data loggers, used in turn to assess conditions and improve performance; such as in air craft maintenance, where tightening of bolts is necessarily done to specific torques (Baber, 2001). In a firefighter context, an oxygen tank could inform the user that it is correctly filled and fitted for use via a HMD. Though with reliance on a system also a concern, these checks would likely not preclude manual checks, but rather be additional to them.

2.1.3. Ergonomic and Interface Concerns

From a design perspective, an intriguing concern with HMDs is the extent to which the wearable must contain the processing power to complete all its functions, or if a connection to other processing sources or networks will suffice (Baber, 2001), with the concern being around the bulk and weight of the system. Though, again, the continually shrinking size, power needs and ever increasing capabilities of wearables are reducing these concerns (Weiland et al., 2000). Along with these physical limitations, psychological concerns also arise, such as how to present information, and timing of information display. These are some concerns for manufacturers, developers, and users of wearable computers. For example, in binocular displays, response times were faster and fatigue symptoms lower when both eyes looked at a single screen, as opposed to having a screen for each eye, either where the left eye looked at a left-hand screen or the left eye looked at a right-hand screen and vice versa for the right eye (Shibata, 2002). Moreover, manual interactions could concern wearable designers; creating more natural interaction should be the ultimate goal. From this perspective, unlike novel gesture interactions, speech is likely the most natural way to interact with wearable computers, and might be able to compensate for many of the typical challenges of completing wearable computer tasks and other tasks at the same time (Witt, 2007). Though, this is perhaps only for some settings (e.g. not for social settings). These psychological concerns should be of particular interest to designers concerned with modality effects, as well as for users in hazardous environments. Bearing in mind that HMDs and wearable computers likely have benefits over other conventional technology, including improved situational awareness, along with a less invasive nature.

Wearable computer users are likely to complete more than one task at a time, a primary real world task—likely moving around—and a secondary wearable task (Witt, 2007). Given the costs of dual-tasking (described below) this is problematic. Additionally, there are a host of other ergonomic concerns associated with these types of wearable computers. For example, HMDs appear to impact tasks through increased head movement, competition for visual attention, and may actually decreases, not enhance, situational awareness (Baber et al., 1999), They can also affect the relation between working sequence and the information displayed (Baber, 2001). Nonetheless, not all effects of using wearable computers are negative. In one study, though it had a small sample size, 70% of participants using HMDs noticed a waving experimenter when walking and reading a news article, compared with 0% of participants using a mobile phone (Orlosky, Kiyokawa, & Takemura, 2014). However, other authors conjecture that with a monocular display, users may find it difficult to share attention between the display information and information from the free eye (Baber, 2001). Although, Orlosky et al. (2014) did use binocular semitransparent displays, with participants both objectively and subjectively better able to view their surroundings. Therefore, the switching between focus of the display and real world stimuli may not be so problematic.

Environment awareness is not the only concern. After wearing a fully immersive HMD, participants had reduced accommodation times from near-to-far and far-to-near adjustments as well as increased subjective eye strain and other eye fatigue (Shibata, 2002). These results raise questions of the long term physiological effects of HMDs. None of this is to mention other possible negative sides of these technologies including malicious or even accidental breaches of security and privacy (particularly concerning in military contexts; Weiland et al., 2000), although this is not an area of focus for this research. This research is principally concerned with questions around the costs of using HMDs in working environments, particularly hazardous ones, thus, the focus on dual-tasking, specifically following the research of Darling & Helton (2014), Green, Draper, & Helton, (2013), and Green & Helton (2011).

2.2. Dual-Tasking

There is a long history of dual-task research beginning as early as 1887 (Woodworth & Schlosberg, 1955). Given the general conclusion that performance deteriorates under dual-task conditions (Bourke, Duncan, & Nimmo-Smith, 1996; Wickens, 1976, 2002, 2008), a specific danger arises in high-risk applied contexts (Helton, Green, & de Joux, 2013), as well as in more quotidian situations, such as driving (Strayer & Drews, 2006). Driving while conversing can be facile in good conditions, while in poor conditions drivers will usually need to solely focus on driving to avoid crashing (Helton et al., 2013). Cell phone use can suppress information necessary for the safe operation of a motor vehicle, and can impair information encoding as well (Strayer & Drews, 2006). HMDs (Google Glass in this case) have been found to also impair driving, though not as much as texting (Sawyer et al., 2014).

Often dual-tasks will have a primary and secondary task, with primary tasks regularly being the more risky or dangerous. In the above examples driving would be the primary task while conversing would be the secondary task. In a climbing dual-task, climbing takes precedence as the decrement in performance is greater for word recall than for climbing, even when participants are not instructed to prioritise one task or the other task (Darling & Helton, 2014; Green et al., 2013; Green & Helton, 2011; Helton et al., 2013). Given the safety concerns associated with falling while climbing, this makes sense. Further, given that even simple games (Drugge, Nilsson, Liljedahl, Synnes, & Parnes, 2004; Nilsson, Drugge, Liljedahl, Synnes, & Parnes, 2005; Witt, 2007) or cyclical walking (Mustonen et al., 2013; Yogev-Seligmann et al., 2010) can be impacted by secondary tasks, the effects of dual-tasking on climbing, which is probably more demanding, are put further into perspective.

2.2.1 Multiple Resource Theory

Multiple resource theory (Wickens, 1976, 2002) is a theory employed to explain multiple task performance. It defines separate resources according to several dichotomies: codes, spatial vs. verbal; modalities, auditory vs. visual; stages, perceptual vs. cognitive; and responding, manual/spatial vs. vocal/verbal (Wickens, 2008). Multiple resource theory is closely related to attention and work load (Wickens, 2002). It contributes importantly to predicting dual-tasking costs and is one of the theories considered in the current research.

2.2.2 Attention

Attention is also an important consideration in dual-tasking. Where as working memory is information stored in an active state in the brain, attention is the information processed at any given moment (Dukas, 2004). This could be sensory input cognitive processing, memory encoding, visual searching and many other tasks. Limited attention means the brain has a restricted amount of information it can process or a restricted rate of processing (Dukas, 2004). Because people have a large number of sensors for attaining information (Carew, 2000), and because during a task people are usually receiving a large amount of sensory information, this can lead to overload (Helton et al., 2013). This overload can limit attentional resources, which leads to a constraining of skill based behaviours (Dukas, 2004). Thus, the addition of a secondary task to attention demanding tasks should deteriorate performance in those tasks. Furthermore, according to multiple resource theory, the compartmentalization of the human cognitive systems means tasks sharing a similar channel of sensory input will interfere with each other more (Wickens, 2002). This does not rule out the existence of a central resource necessary for all tasks, which if over stressed could result in task deterioration (Helton et al., 2013; Wickens, 2008). For example, even though climbing is primarily a spatial and visual task, a secondary audible word recall task created significant dual-task interference (Green et al., 2013; Green & Helton, 2011). Indeed, other research identifies the severe limitation in performing simultaneous mental operations in general, with the positing of central bottlenecks (Pashler, 1994). Multiple resource theory contributes importantly to predicting decrements in mental workload when there is overload imposed by two or more tasks (Wickens, 2008). Wickens (2008) connotes that tasks with a greater over-lap in resources (qualitatively) see a greater decrement in performance.

2.2.3 Task Difficulty

Automated, or well practiced, processes may require less attentional resources allowing for more to be used on a secondary task (Dukas, 2004). Some examples include experienced footballers (soccer players) having no detriment to dribbling when dual-tasking (Beilock, Carr, MacMahon, & Starkes, 2002), and no change in performance in a verbal fluency task when dual-task walking (Yogev-Seligmann et al., 2010), even when fluency was explicitly prioritised. Yet, studies suggest walking (Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997; Yogev-Seligmann et al., 2010) or even computationally simple tasks (Pashler, 1994) can be susceptible to dual-task interference. Much work in dual tasking has been carried out on walking while completing another task. Results suggest executive function and attention affect gait (Yogev-Seligmann et al., 2010). Performance of visual tasks decreased walking speed and increased errors (Mustonen et al., 2013), while gait speed is lower when dual-tasking as opposed to just walking (Yogev-Seligmann et al., 2010). Further, paced walking impairs performance in vigilance and working memory tasks (Mustonen et al., 2013). Indeed, even standing posture is affected, in some instances, by a secondary (cognitive) task (Jamet, Deviterne, Gauchard, Vançon, & Perrin, 2007). Increasing task difficulty, such as adding obstacles to walking routes, increases dual-tasking costs (Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008). Yet, Siu and colleagues also found no change in gait under some dual-tasking conditions, indicating prioritisation of walking in these conditions. This result could be owing to difficulty insensitivity; difficulty insensitivity being where one task fails to degrade the performance of another (Wickens, 2008). An example of this is people carrying out unrelated central processing such as memory retrieval while monitoring sensory input at a simple level (Pashler, 1994). Though initially demanding, tasks can become more automated, allowing for increasing speed and then signal detection (Helton, 2007), however, even after extensive training, secondary tasks can still affect primary tasks (Huemer & Vollrath, 2012). As an aside, dual-taking affects improvements from practice. Training effects occur more slowly when task are performed simultaneously (Huemer & Vollrath, 2012), illustrating the wide ranging detriment dual tasking can have.

Previous research indicates that having a cell phone conversation disrupts drivers' ability to pay attention to their environment or create durable memories of environments (Strayer & Drews, 2006). Due to the danger involved in losing control of a motor vehicle—crashing—it is pertinent not to use a cell phone while driving. Certainly, this is why in many countries have banned cell phone use while driving, including New Zealand and Australia. It is also expected that when driving minimal distraction by in-car systems will occur, because of dual-tasking costs (Huemer & Vollrath, 2012). This includes cognitive distraction, not just manual distraction since, distraction from cell phones persists, even when manual sources of interference are removed (Strayer & Drews, 2006). This is also imperative in the context of jobs, and is especially true of hazardous occupational environments such as military, firefighting, police and search and rescue. These hazardous environments can include the use of high angle climbing; part of the reason that climbing has been studied in the past (Darling & Helton, 2014; Green et al., 2013; Green & Helton, 2011; Helton et al., 2013). Climbing is a demanding task where climbers are receiving a large amount of sensory information, which can lead to overload (Helton et al., 2013). Research on the physiology and psychology of sport climbing has been increasing over the past years, including some on dual-task climbing.

2.3. Climbing

The popularity of sport climbing has increased over the past 20 or so years (Sheel, 2004). This is part of the reason there has been an increase in research on climbing. The practical applications of understanding climbing physiology and psychology are also important, particularly for work such as search and rescue. Climbing consists of a series of static and dynamic phases where one moves horizontally or vertically on the climbing face (Bourdin, Teasdale, & Nougier, 1998). Within these motions the legs mainly support weight while the arms essentially stabilise posture (Quaine, Martin, & Blanchi, 1997).

There are many different styles of climbing which include: top rope climbing, where the climber is protected by a rope that passes through an anchor atop the wall and back to the belayer; Lead climbing, where the rope is clipped through a series of anchor points along the route supporting the climber; Seconding, where the climber follows a lead climber removing the anchors as they go; Free climbing, where the ascent is made without protection; and Bouldering, another form of free climbing usually done on shorter routes and often with the protection of a bouldering mat (Draper, Jones, Fryer, Hodgson, & Blackwell, 2010). Of these on-sight (where a climber makes an ascent without prior knowledge of the route) lead climbing is seen as the purest form of climbing (Draper, Jones, Fryer, Hodgson, & Blackwell, 2008). Lead and top roped climbing would likely parallel most closely the style of climbing search and rescue workers do. Even so, bouldering is the easiest of the climbing varieties to look at in a research context. This is due to safety as there is a low height and large padded bouldering mats used to cushion falls, furthermore a rope and belayer are not necessary. This makes it easy to assess controlled cognitive tasks or other tasks in the context of rock climbing. Bouldering has been used before in this type of psychological research (Darling & Helton, 2014; Green et al., 2013; Green & Helton, 2011), though other more physiological research has focused on lead climbing (Draper et al., 2008, 2010).

2.3.1 Physiological and Psychological Demands

Climbing is both a physiologically and psychologically demanding task, requiring a high level of relative strength (Morrison & Schöffl, 2007). Rock climbing requires a large proportion of the body's aerobic capacity and harder climbs likely require anaerobic systems as well (Sheel, 2004). Heart rate also increases with climbing difficulty (Sheel, 2004). Heart rate and VO_2 increases are slightly (though not significantly) larger when the climber is unfamiliar with the route; unfamiliarity with the route can also be more anxiety provoking than a subsequent climb of the same route (Draper et al., 2008). Given that emotion can affect motor performance in simple tasks such as tracing (Coombes, Janelle, & Duley, 2005) and reduce efficiency in climbing tasks (Green et al., 2013), we might expect climbers with less familiarity with the route to perform worse. Route unfamiliarity would be common in urban search and rescue operations where collapsed buildings would each provide novel routes. Search and rescue operations might also involve descending then ascending a climbing—ice or rock—face to rescue an accident victim (Helton et al., 2013) where rescuers are not familiar with the routes. Draper et al. (2008) also reports that an initial on-site lead climb was significantly slower than a subsequent climb of the same route. They attribute this to time taken to plan routes. With the addition of HMDs to search and rescue, firefighting and other hazardous work (given both the psychological and physiological demands expressed here) and where these technologies might be cognitively or emotionally invasive, their use may be injurious to performance.

2.3.2 Attentional Demands

Climbing is a sport with a high attention demand. Static position climbing requires more attention resources than standing, with more difficult climbing postures requiring more attention resources (Bourdin et al., 1998). These high attention demands appear susceptible to interference, affecting planning. Probing participants prior to, or after climbing movements decreases reaction times, likely meaning that the planning for the second movement occurs at the end of the first, rather than a new programming or planning phase (Bourdin et al., 1998). This interference with climbing performance is troublesome, given that in recreational climbing a climber would be in contact with their belayer about rope tension (Green & Helton, 2011; Helton et al., 2013), while high angle rescue operators communicate with their teams to coordinate efforts or receive radio transmissions for improved situational awareness (Helton et al., 2013). Past research has certainly suggested that there is significant interference with climbing performance when a secondary task is also conducted (Darling & Helton, 2014; Green et al., 2013; Green & Helton, 2011; Helton et al., 2013). Further, emotionally negative (fear) words produced a greater decrement in distance covered and efficiency while climbing, compared with both a single climbing condition and another non-fear word condition (Green et al., 2013). Participants in these experiments were also asked to recall words later that were presented to them as they climbed. Again, interference in word recall was found, with significantly less words remembered when climbing (Darling & Helton, 2014; Green et al., 2013; Green & Helton, 2011; Helton et al., 2013). Given the interaction of a secondary task or probe with performance and reaction times, a consideration of the effects of interrupting a primary task needs to be made.

2.4. Interruptions and Warning Systems

Wearable computers would likely employ a system to warn the user when information is presented, or when it changes. In search and rescue, additional information about victim location or weather changes could be signalled to the user, more mundane users will likely be signalled about messages or emails. However, warnings (likely being of audible, tactile, or visual nature in a HMD context) constitute interruptions of the primary task; not so bad for simple tasks but could be more detrimental if the task is dangerous. Interruptions can have major implication in aviation, emergency response work, and hospital settings (Trafton & Monk, 2007). In one experiment, participants watched a video and were interrupted by a secondary 30 second video of spoken text or of silence, then were required to recall information from the primary video; participants made errors from previous knowledge rather than the interruption task (Oulasvirta & Saariluoma, 2004). From this, the researchers concluded that the encoding of information into long term memory is affected by interruptions. Contrastingly, in a dual-task, Darling & Helton (2014) found climbers made free associations with nearly all the words in a seated condition and a climbing dual-task condition. They suggest, from their findings, that interference occurs in the rehearsal and maintenance of words or at more elaborate encoding stages, rather than not encoding the words. There is some issue with comparability between these two tasks, given that one was a primary and the other a secondary task. Still, other research concludes that initial encoding of information is impaired (Strayer & Drews, 2006).

After an interruption it can be quite difficult for people to resume the primary task from where they were interrupted (Trafton & Monk, 2007). For example, in a climbing context, if a person had planned a route, an interruption may affect this plan making the climber change or re-plan their route, slowing the climb. Alternately a step of a previous plan might be skipped (Trafton & Monk, 2007). Thus, it would be expected that wearable computer systems, particularly those used in hazardous work contexts, would be designed to be as minimally disruptive as possible. Typically, an auditory interruption stimulus appears less detrimental to a primary task than a visual interruption stimulus (Witt, 2007), which is in line with multiple resource theory. However, responses to visual signals are faster than auditory signals, suggesting visual signals outweigh auditory ones (Chan & Chan, 2005). Further, when presented together, visual signals show a superiority effect over auditory signals (Lee & Chan, 2008). Contrarily, participants completed more secondary tasks with audible warnings compared to visual warnings, and performance generally appeared better with an audible warning system compared to a visual one, though these results were not significant (Drugge et al., 2004). Other research has found auditory alerts to be marginally significant in their efficacy over visual alerts (Wickens & Colcombe, 2007). Thus in some cases audio warning signals can induce better performance even if they are some times less liked and subjectively more stressful than visual signals (Nilsson et al., 2005). Whether this holds for physical activities is less clear.

Objective performance measures and subjective preferences can differ where interruption and warning signals are concerned, and these need to be taken into account when designing systems where interruptions are necessary (Nilsson et al., 2005). McFarlane (2002) found participants preferred negotiated interruptions (where the secondary task could be put on hold) for signalling and completing a secondary task. This is not always possible, especially where instant information processing is necessary for safety.

While visual warning signals might be better in some ways, auditory warning signals appear less disruptive, making them more useful in dangerous contexts. Additionally, with highly visually demanding primary tasks, an auditory stimulus should interfere less, according to multiple resource theory (Wickens, 2008). Another interruption and interference theory, from Trafton, Altmann, Brock, & Mintz (2003) defines lag phases between the alert for the secondary task and the beginning of that task, followed by another lag between the end of the secondary task and the resumption of the primary task. Thus, more interruptions result in more lag phases, slowing performance. Interruption effects might be reduced with appropriate timing of secondary tasks, as people generally perform better where they can negotiate interruptions (McFarlane, 2002). Yet, dual-tasking costs are not necessarily affected by temporal unpredictability of the secondary task (Koch, Metin, & Schuch, 2003). Also, where quicker initiation of the secondary task is necessary (for safety), immediate interruption might be better (McFarlane, 2002). The right kind of interaction modality (such as speech rather than novel gestures) might be able to compensate for many of the typical challenges of dual-tasking and interruptions (Witt, 2007). Some evidence for this being that speech based text entry is better than manual text entry, though both are still worse than a single task condition performance (He et al., 2014). Warning systems are also usually better when they are reliable (Helton, Head, & Russell, 2011) and perfectly predictive (Finkbeiner, Wilson, Russell, & Helton, 2014). Thus, a perfectly predictive warning system, with an audible signal or cue for information presentation, should be the best option for using HMDs in hazardous environments.

2.5 Research Outline

Given the application of HMDs to emergency response work, we examined the use of HMDs on climbing, as well as the effect of an audible warning system, using a dual-task paradigm. Five conditions were used: a seated word recall condition with no audible warning of word presentation, a seated word recall condition with a perfectly predictive audible warning of word presentation, a dual-task climbing condition with no audible warning of word presentation, a dual task climbing condition with a perfectly predictive audible warning of word presentation, and finally a climbing only condition. This research is particularly interesting as little work seems to have been done on the cognitive casts of climbing (Green & Helton, 2011), and as far as we can tell none with HMDs.

2.5.1 Hypotheses

Hypothesis 1 - Climbing performance (distance and efficiency) will be significantly worse in a dual-task context relative to a single task climbing context.

Hypothesis 2 - Information recall from a dual-task context will be significantly less than in a single task recall setting.

Given the costs of dual-tasking, we expect the use of wearable computers, and HMD in this case, to negatively impact climbing performance in a dual-task context as well as information recall. Both distance and efficiency (holds per meter) should be worse under dual-task conditions, given the physical, psychological and attentional demands of climbing. Also, participants should recall fewer words in the dual-task condition relative to the single task word recall conditions.

Hypothesis 3 - An audible warning signal should increase the information seen under dual-task conditions compared to no warning signal.

Hypothesis 4 - An audible warning signal should increase the information recalled under dual-task conditions, comparative to no warning signal.

The literature on interruptions and warning signals implies that warning signals can improve attendance to a secondary task. However, the effects of audible warning signals on climbing performance are unclear, from this literature. Thus, the effect of a warning signal on information recall (words recalled) was drawn more tentatively than for information actually seen (words read aloud).

Hypothesis 5 - There will be significant differences in reported mental, and physical, demand, and fatigue, in the dual-task conditions relative to the single task conditions.

Because of the demands of dual-tasking, physical and mental effort and fatigue under dual-task conditions should be greater relative to single task conditions. Obviously, participants should find seated conditions less physically demanding than climbing, while dual-tasks should be more mentally demanding than single tasks. Dual-tasks also likely require more concentration, and participants should be thinking more about the task (higher task related thoughts) than unrelated information (lower task unrelated thoughts).

Hypotheses 6 - Participants should be slower at times when information was presented compared to when information was not presented, under dual-task conditions.

According to Trafton et al. (2003) and Trafton & Monk (2007) around word presentation times is where lag phases occur which will produce slower times around word presentation (as long as participants are attending to them). Alternately, according to multiple resource theory (Wickens, 2002, 2008) this is where overlap for visual resources occurs, which would likely decrease speed. Multiple resource theory would also predict that the cognitive aspect of word rehearsal and elaborative encoding would interfere with the cognitive aspects of climbing (route planning), slowing climbers.

We also looked to compare our results with other research, on at least a face value level. We wanted to see how the use of a visual presentation of information differed from the audible presentation used in previous research. Multiple resource theory would imply that a visual task would interfere more with climbing than an audio task. Additionally we wanted to see how complex physical tasks related to stationary and seated tasks.

3. Method

3.1 Participants

Participants were recruited through a posting on a research recruitment website, social media, word of mouth, advertisements at the University of Canterbury Recreation Centre, and through the University of Canterbury Climbing Club.

A total of 22 participants were recruited through the above methods, and of these, three participants were removed for lack of climbing ability. Using the climbing alone condition as a measure of base ability, these participant were found to be outliers. The average participant age of the remaining 19 participants, of which five were female, was 22.5 years with a range of 18 to 35. All participants had normal eye sight.

Participants had varying ranges of climbing ability, but were required to be capable enough that they could boulder along the climbing wall for a five minute duration, not falling too often during this time. Participants were not included if they spent too much time on the ground or were not able to complete all conditions (see outliers above). These requirements are similar to those applied by Darling & Helton (2014).

3.2 Materials

The experiment was run at the University of Canterbury Recreation Centre climbing wall. This is a textured wall surface with bolt on artificial holds of many shapes and sizes; additionally the texturing simulates more natural climbing features that could also be used as holds. Ropes were not used, as participants were bouldering or traversing the climbing wall below a height of approximately 3.3m. This is the safe free climbing height allocated by the Recreation Centre and is marked with red tape on the climbing wall, participants were instructed to stay under this for the duration of the climb. The climbing surface is displayed in Figure 3 below.

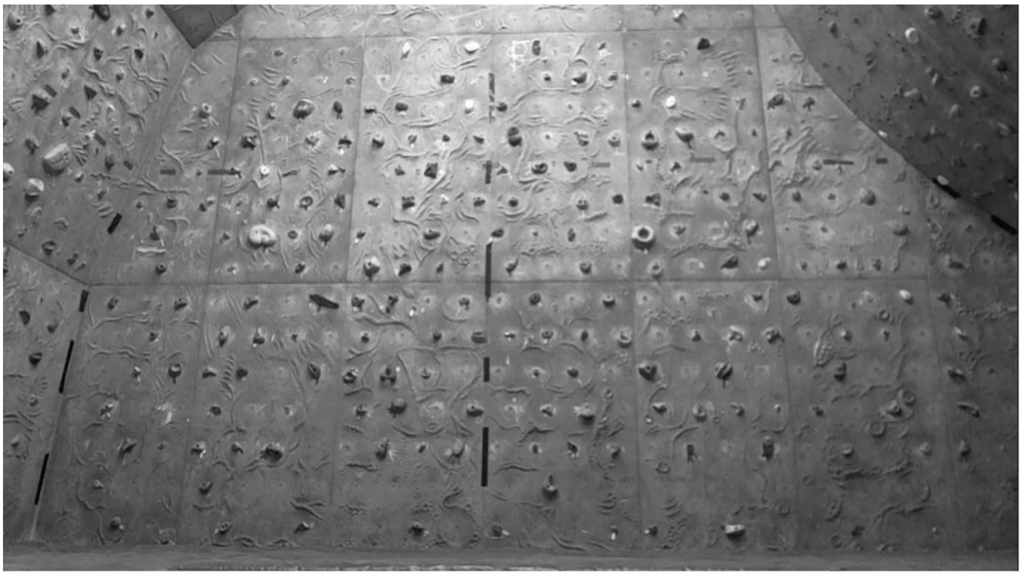

Figure 1. Image of the climbing surface used in the experiment, see Darling & Helton (2014), Green et al. (2013), and Green & Helton (2011) for additional images.

Figure 2. Google Glass With Frame for Prescription Lens by Mark Panhu. Retrieved from http://en.wikipedia.org/wiki/File:Google_Glass_with_frame.jpg. Used under the Creative Commons Attribute-Share Alike 3.0 Unported Licence http://creativecommons.org/licenses/by-sa/3.0/deed.en.

The head mounted display used for this experiment was the Google Glass explorer edition (www.google.com/glass/start/, also see Figure 1 above). This is a monocular see-through display that sits just above the right eye, slightly outside of the user's central vision. The position of the Google Glass above the eye depended on the facial structure of the user, and so varied from participant to participant. A version of the frames with a set of non-optical "lenses" was used to add protection for participants' eyes. The display screen is 640×360 pixels, and is projected through an optical prism, which, from the users perspective, is the equivalent of a high definition 25 inch display viewed from 8 feet away (Google, 2014).

A program was developed, in the Processing programming language (Fry & Reas, 2001), for the Google Glass device that displayed a list of 19[1] words over an approximate five minute period. This period was divided into 14 second blocks with a 10 second period at the start of the trial; this gave participants a chance to ease into the rhythm of climbing. Words were displayed for two seconds at random times within the 14 second blocks after this 10 second period. The program also randomized the word order for each trial. The words used for this experiment were taken from the Paivio, Yuille, & Madigan (1968) word pool. This is a list of 925 nouns all rated on Frequency, Imagery, Concreteness, and Meaningfulness. Using an online generator (Friendly, 1996), four word lists were generated (see Appendix A), with the parameters: Frequency 0-40, Imagery 5-8, Concreteness 5-8, Meaningfulness 5-8, Syllables 2-8, and Letters 5-8.

A Logitech HD Pro Webcam C920 was used to record climbers. The videos taken of climbers were used to count the number of holds used and the distance covered along the wall. From these measures, we assessed climbing performance by looking at differences in

[1] This was originally intended to be 20 words but due to an error the program omitted one word every trial. Due to the programs ordering of the lists this was random every time.

distance covered and efficiency (holds/m) between conditions. The video was recorded directly onto a laptop from the webcam, and audio was recorded via an external microphone. An AZDEN WMS-PRO VHF wireless microphone system, housed in a back pack, was used to record participants' responses to words. The backpack that housed the microphone relay was also used to mount a ball for motion tracking. Using a free and open source program called Kinovea (n.d.), we tracked the motion of the climbers. To assess motion during word presentation, we took a sample of the motion tracking data from a 4 second period (2 seconds before and 2 after) around the time words were presented and equivalent samples at non-word climbing periods.

Participants completed paper copies of questionnaires after the word recall section of each condition. This questionnaire combined questions of a modified NASA TLX (Hart & Staveland, 1988) and assessed mental and physical intensity of each condition. Several 0 - 100 visual analog scales (See appendix B) were used to allow participants to indicate how they experienced, both mentally and physically, these various conditions.

3.3 Procedure

Upon arrival at the climbing centre, participants were given an information sheet to read. This sheet contained an outline of the experiment, some instruction for the experiment and safety information regarding the climb and the wall (see Appendix C). Participants were informed that they would complete five conditions, three climbing conditions and two seated, and that there would be a mandatory 4 to 5 minute rest period between each condition (though, any extra additional rest time was allowed). Conditions were randomly ordered and counterbalanced, so as to reduce any order bias. A pre-questionnaire was also administered after the information sheet was read and consent form signed. The pre-questionnaire asked participants to report on thoughts and feelings in the last 10 minutes, prior to arriving at the experimental location. Participants brought their own climbing shoes if they wanted to use them. A warm up period was given where the climbers could gain familiarisation with the wall, its holds, and the layout, before undertaking the experiment, done to reduce the effects of unfamiliarity with the route (Draper et al., 2008).

3.3.1 Seated Conditions

Each seated condition consisted of a participant sitting on the edge of the bouldering mat, for the duration of the condition. They then proceeded to select the word list they were using with the Glass display via the touch pad along the side of the device; prior to commencing any conditions, participants were instructed on how to interact with the Google Glass device. The list of 19 words was displayed over an approximate 5 minute period at random times within 14 second intervals with a 2 second break between each interval. This meant that words were presented at around a maximum of 26 seconds apart and a minimum of 2 seconds. A buzz sound indicated both the beginning and end of each condition. Participants were informed of this and told that after the end of each condition (indicated by the final buzz) they would have a minute and a half period to recall as many words as possible, which were written on paper forms provided by the experimenter. Word recall was followed by the questionnaire. Additionally, one of the seated conditions had an auditory warning (a monotone beep) which preceded word presentation. This tone began half a second before the word appeared and lasted for half a second. In contrast the second seated condition had no auditory warning prior to word presentation.

3.3.2 Dual-Tasks

For the two climbing dual-tasks participants also selected the condition via the Google glass display. While selecting the condition, participants stood on the ground in front of the climbing wall at the far left hand side and once the program buzzed (indicating the beginning of the condition) they took a hand and foot hold on the left side wall adjacent to the main climbing wall, while the other two limbs took holds on the main climbing wall.

Participants began climbing straight after this set motion, which in practice was more fluid than the description illustrates. Participants were instructed that they were allowed to use any hold on the wall including the natural features of the textured wall, so long as they stayed below the 3.3m safe free climbing height, indicated on the climbing wall by dashed red tape. The traverse continued until participants reached the seventh panel of the wall having been told to take separate hand and foot holds on that panel, then traverse back the other way. Once participants reached the end they began at, they took separate hand and foot holds on the adjacent wall then climbed back towards the other end again. This same pattern recurred for the duration of the 5 minute climbing conditions, the end of which was indicated to participants via the same buzz noise from the beginning of the conditions. Participants were instructed to stop traversing and drop off the wall after this second buzz. Finally, participants were instructed that if they came off the wall to get back on at approximately the location where they fell and continue the traverse. During the traverse participants were played the list of 19 words on the Google Glass display over the 5 minute period in the same way as in the seated conditions. Like the seated conditions one of the dual-task climbing conditions had an auditory warning (a monotone beep starting half a second before word presentation and lasting half a second) preceding word presentation, with the other having no auditory warning. Finally, like seated conditions, participants completed the word recall form and then a questionnaire following each condition.

3.3.3 Climbing Only

The third climbing condition, the climbing only (or alone) condition, followed the same procedure as the dual-task climbing conditions apart from the word lists. In this condition participants were presented a list of scrambled letters on the Google Glass display, for continuity. Participants were instructed that they did not have to read these non-words, nor remember them, nor look for them. After this condition participants were given a 90 second wait period, in lieu of word recall, before answering the questionnaire, done to keep timing consistent across all conditions.

3.3.4 Filming

All of the climbing conditions for all participants were recorded using a HD web camera. This was done firstly to code participants on climbing performance (distance and holds) and secondly to get motion tracking data via a video analysis tool called Kinovea (n.d.). For this, participants wore a backpack with a yellow ball in the middle. The ball was fixed to the bag with Velcro and was thus consistently and similarly placed on the bag across participants. This ball was the fixation point to track in the motion tracking program. Some adjustments were made to the tracking path if the participant turned the ball away from the camera, or exited the field of view. The camera was set at approximately 6.1 meters from the wall, at a height of 0.5 meters, and remained stationary for the duration of each participant's trials.

3.3.5 Motion Data

For the motion data a 720p video of each participant's climbing conditions was taken. To standardise this, we placed the camera in approximately the same location for all participants, though not exactly, due to manual positioning of the camera, and remained in the same location through all conditions. A single participant did not have motion data to contribute due to a technical difficulty rendering the backpack, carrying the motion tracking ball, inoperative leaving 18 participants contributing motion data. The backpack was worn by all participants who were instructed to tighten the pack as much as possible, but not so much that it would affect their climbing performance. This afforded some degree of consistency regarding the position of the ball, which accordingly did not swing about but followed each participant's motion.

Kinovea, (n.d.) gave the X and Y coordinates (relative to a set position in the corner of the cameras field of view) for each participant at intervals of 40 to 160 milliseconds. Thus, some measures were 40-120 milliseconds off time, because of missing data points from the program. Nevertheless, because the data was a ratio of distance to time (speed) and averaged over several samples, this error should have minimal impact. From the dual-task conditions, a four second sample (two seconds before and two seconds after) was taken from around the time participants saw each word. This sampling was not done if participants were on the ground during word presentation. The number of samples around word presentation were dependent on the number of words participants saw, thus they varied between participant and conditions. From this dual-task motion data we also took 4 second samples outside of word presentation typically taken from between word presentation. Where this was not possible, some periods between words seen were sampled twice, with no overlap. Nineteen samples were taken for all participants outside of word presentation, in both dual-task conditions. For the climbing alone condition, the timing of word presentation was averaged across the two dual task conditions, and adjusted where there was overlap and redundancies. Again, 19 samples were taken for each participant in the climbing alone conditions, which was assumed to be representative of the whole condition.

The speeds appear to be consistently slightly faster when taken from the motion tracking program rather than using manual distance calculations. This is likely to do with the cameras distance from the wall and angle to the edges of the climbing face, both necessary to enable motion tracking. Additionally, the 4 second times were slower than the single second samples. This is likely due to how participants move as they climb; motion is not consistently forward, but rather dynamic in direction so as to get to appropriate holds. Finally, the omission of one participant due to gear malfunction may have contributed to these discrepancies. To calculate speed, the difference between the start and the end of the time period (one or four seconds) was taken. This was converted into a positive distance where necessary, then averaged across all the samples taken.

Kinovea (n.d.) was used as the tracking program due to the free and open source nature of the program, allowing easy replication of this research. Manual adjustments could also be made if the program made errors, or the tracking object was removed from the field of view. There are questions as to the accuracy of the program, which is relatively unknown, though it has be used in some biomechanical research before (Guzmán-Valdivia, Blanco-Ortega, Oliver-Salazar, & Carrera-Escobedo, 2013; Vladimir, Carmen, & Andreyeva, 2014). Additionally the measures taken for assessing the motion data all came from Kinovea (n.d.) thus, any error should be consistent across all participants and trials. Given these parameters for the motion tracking program, we were confident our data could provide some useful insight.

3.3.6 Debrief

As a final step after completing the experiment, participants were informed of the purpose of the research and what was expected of the outcomes. Further, they were offered the opportunity to receive the results of the experiment if they wanted. Finally, participants were given the opportunity to ask any questions about the research.

4. Results

4.1 Climbing Performance

Two one-way repeated measures ANOVA were completed on climbing efficiency (holds per m) and climbing distance (m). The three climbing conditions were compared: climbing alone, climbing with word recall and no signal, and climbing with word recall and a pre-emptive auditory signal. The ANOVA was significant for climbing efficiency, $F(2, 36) = 5.07$, $p = 0.012$, $\eta_p^2 = 0.22$, and for distance covered, $F(2, 36) = 5.50$, $p = 0.008$, $\eta_p^2 = 0.23$.

Pre-planned orthogonal contrasts were used, firstly to compare the climbing alone condition with the two dual-task conditions combined, and also to compare the two dual-task conditions. Efficiency was better in the climbing alone condition (M = 6.40, SE = 0.43) than the combined dual-task conditions (M = 6.87, SE = 0.50), $t(18) = 3.04$, $p = 0.007$, $d = 0.23$, however, there was no difference between the two dual-task conditions, $t(18) = 1.57$, $p = 0.13$. Further, climbers covered more distance in the climbing alone condition (M = 31.71, SE = 3.71) than the combined dual-tasking conditions (M = 28.92, SE = 3.49), $t(18) = 2.77$, $p = 0.013$, $d = 0.18$. Again there was no difference between the two dual-task conditions, $t(18) = 1.13$, $p = 0.28$.

4.2 Word Task

For word recall we were interested in the effects of dual-tasking as well as the auditory warning system and the potential interaction that a warning system might have on both word reporting (reading the words seen) when climbing, and word recall after climbing. For this, we conducted two, two by two repeated measures ANOVA consisting of the warning signal vs. no warning signal conditions and the dual-taking vs. seated conditions for both words seen and words recalled.

For words recalled, the only significant result from this test was the dual-task vs. single task conditions, where more words were recalled in the single task conditions (M = 14.13, SE = 0.65) than the dual-task conditions (M = 7.71, SE = 0.82), $F(1,18) = 80.52$, $p < 0.0001$, $\eta_p^2 = 0.82$. The rest of the results were non-significant (Signal Vs. no signal $F(1, 18) = 2.32$, $p = 0.15$; Interaction $F(1, 18) = 0.32$, $p = 0.58$). Figure 3 displays this relationship.

For words seen there were significantly more words seen when an auditory warning was present (M = 18.97, SE = 0.03), than when no warning was present (M = 16.92, SE = 0.47), $F(1, 18) = 18.85$, $p < 0.001$, $\eta_p^2 = 0.51$. Moreover, more words were seen in the seated conditions (M = 18.92, SE = 0.48) than the climbing conditions (M = 16.97, SE = 0.06), $F(1, 18) = 15.54$, $p = 0.001$, $\eta_p^2 = 0.46$. Importantly, there was also a significant interaction effect $F(1, 18) = 14.40$, $p = 0.001$, $\eta_p^2 = 0.44$, which is displayed in Figure 4.

We can see from the estimated marginal means in Table 1 and from Figure 4 that the number of words seen is dependent on both whether a participant was dual-tasking or not, and if there was an audible warning signal. Thus, the significant main effects of signal vs. no signal in the two by two ANOVA was due to the lower number of words seen in the climbing with no signal condition, where participants saw on average 15 words.

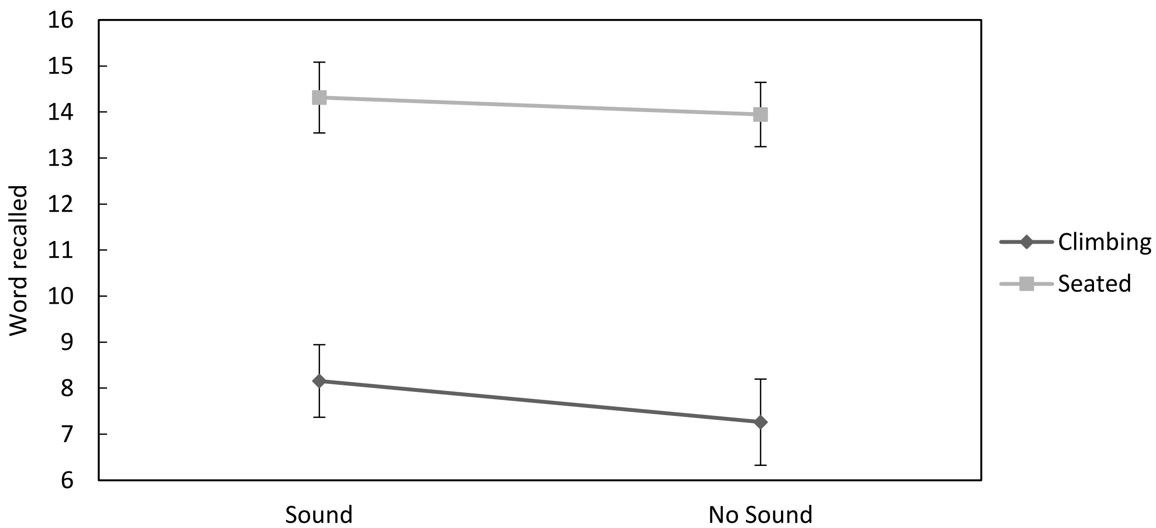

Figure 3. Words recalled separated by condition and signal. Error bars are standard error.

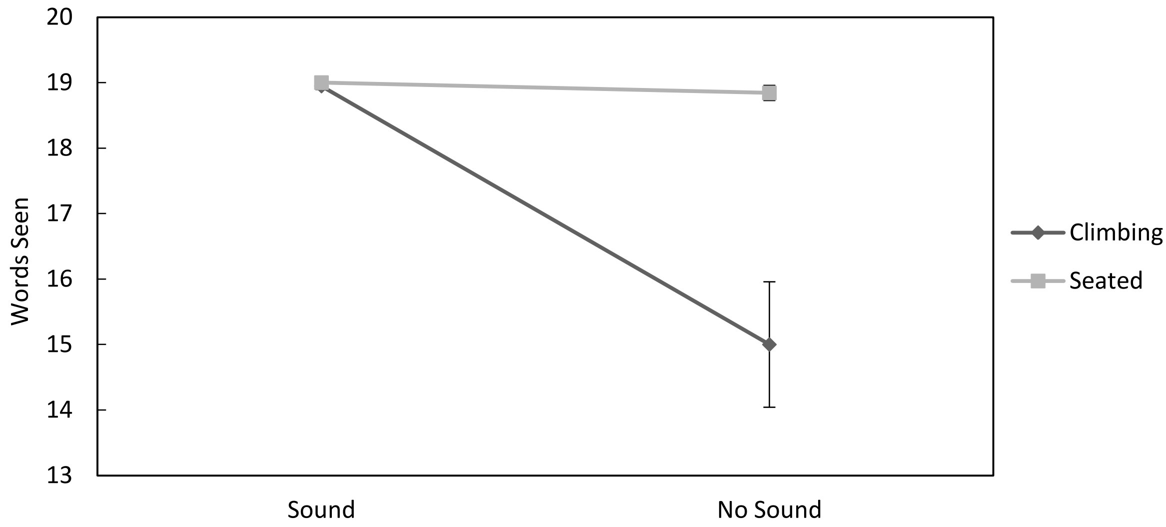

Figure 4. Words seen separated by condition and signal, error bars are standard error.

Table 1.
Estimated marginal means for words seen, for both conditions and warning signal

		Mean	SE
With Sound	Climbing	18.95	0.05
	Seated	19.00	0.00
Without Sound	Climbing	15.00	0.96
	Seated	18.84	0.12

4.3 Self-Reports

For the self-report scales we were interested in comparing the levels of physical and mental demand, physical and mental fatigue, and concentration, participants experienced between the different climbing conditions. Further, on task (task related) and off task (task unrelated) thoughts were also compared. Repeated measures ANOVAs with planned comparisons were carried out. Table 2 displays the means and standard error for the self-report measures.

4.3.1 Mental and Physical Demand

A repeated measures ANOVA was conducted on the self report scores for mental demand and physical demand across the five conditions. The analysis was significant for mental demand, $F(3.20, 57.74) = 26.04$, $p < 0.001$, $\eta_p^2 = 0.59$ (Greenhouse-Geisser correction), and for physical demand, $F(2.31, 41.58) = 106.56$, $p < 0.001$, $\eta_p^2 = 0.86$ (Greenhouse-Geisser correction). Because we were specifically interested in the differences between the climbing alone conditions and dual-task climbing conditions as well as between the single task climbing condition and the single task seated conditions and finally between the dual-task conditions and the single task seated conditions, pre-planned contrasts were conducted. For mental demand there was a significant difference between the climbing alone condition and the combined dual-task conditions, $F(1, 18) = 62.83$, $p < 0.001$, $\eta_p^2 = 0.78$, as well as a difference between the climbing alone condition and the single task seated conditions, $F(1, 18) = 30.16$, $p < 0.001$, $\eta_p^2 = 0.63$. There was, however, no difference between the combined dual-task conditions and the combined single task seated conditions $F(1,18) = 0.063$, $p = 0.805$, and though there was reportedly more mental demand in the no auditory warning dual-task condition this was not significant, $F(1, 18) = 2.29$, $p = 0.148$. For physical demand there was a significant difference between the climbing alone condition and the combined seated single task conditions, $F(1, 18) = 260.11$, $p < 0.001$, $\eta_p^2 = 0.94$, as well as between the combined dual-task conditions and the combined single task seated conditions, $F(1, 18) = 280.30$, $p < 0.001$, $\eta_p^2 = 0.94$. No difference was found between the climbing alone condition and the combined dual-task conditions, $F(1, 18) = 0.09$, $p = 0.770$, or the two dual-task conditions, $F(1, 18) = 0.33$, $p = 0.575$.

4.3.2 Mental and Physical Fatigue.

Participants also reported on their mental and physical fatigue after each condition, as above pre-planned contrasts were conducted. From these scores we found that participants felt significantly more mentally fatigued in the dual-task conditions compared with both the climbing alone condition, $F(1, 18) = 34.76$, $p = 0.001$, $\eta_p^2 = 0.66$, and the single task seated conditions, $F(1, 18) = 5.37$, $p = 0.033$, $\eta_p^2 = 0.23$. Additionally, and obviously, participants reported more physical fatigue in the dual-task climbing conditions compared to the single task seated conditions, $F(1, 18) = 87.18$, $p < 0.001$, $\eta_p^2 = 0.83$, and in the climbing alone condition compared with the single task seated conditions, $F(1, 18) = 86.88$, $p < 0.001$, $\eta_p^2 = 0.83$. Though participants did not report a significant difference between physical fatigue felt in the climbing alone condition and the dual-task conditions $F(1, 18) = 0.17$. $p = 0.897$.

4.3.3 Concentration

Against expectations we found no difference in the contrasts of the repeated measures ANOVA, for concentration, between the conditions; all were above $p = 0.05$. The only significant difference was between the pre-test and the other conditions, $F(1, 18) = 46.66$, $p < 0.001$, however, this result was not of interest to us. These results are especially interesting considering our anticipation that being attentive to pseudo-randomly presented words would require more concentration and attention, especially when no pre-emptive auditory warning is present.

4.3.4 Task Related and Task Unrelated Thoughts

Another set of results that went against expectation were task related thoughts (TRT). For task related thoughts a significant repeated measures ANOVA was found, $F(3.20, 57.56) = 14.84$, $p < 0.001$, $\eta_p^2 = 0.45$ (Greenhouse-Geisser correction), with the only significant differences of interest being between the climbing alone condition and both the combined dual-task conditions, $F(1, 18) = 6.05$, $p = 0.024$, $\eta_p^2 = 0.25$, and the combined seated conditions, $F(1, 18) = 4.97$, $p = 0.039$, $\eta_p^2 = 0.22$, with the climbing alone conditions being lower in task related thoughts than the other conditions. All other results were above $p = 0.05$. The lack of significant findings imply that word recall was the task mostly affecting subjective task related thoughts, as opposed to the climbing task.

For task unrelated thoughts (TUT) a significant repeated measures ANOVA was found, $F(5, 90) = 11.06$, $p < 0.001$, $\eta_p^2 = 0.38$. With the only significant difference of interest being the decrease in task related thoughts between the climbing alone condition and the dual-task conditions, $F(1, 18) = 6.28$, $p = 0.022$, $\eta_p^2 = 0.26$, all other results were above $p = 0.05$.

Table 2.
Means and standard errors for self report scores

	Climb alone		Dual task no signal		Dual task signal		Seated	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Mental demand	46.00	0.92	77.00	0.76	73.00	0.78	73.38	0.79
Physical demand	76.75	0.59	78.25	0.47	76.50	0.80	6.88	0.52
Physical fatigue	60.00	0.83	56.75	0.78	63.00	0.92	13.00	0.61
Mental fatigue	30.50	0.82	53.75	0.93	59.25	1.00	47.00	1.14
Concentration	71.50	0.82	74.50	0.80	75.75	0.87	72.63	0.78
TRT	66.25	1.09	79.75	0.60	77.75	0.73	76.63	0.80
TUT	28.00	1.06	17.50	0.82	18.50	0.63	24.13	0.94

4.4 Motion Data

For the motion data we used participant speed, calculated from the coordinate data given by Kinovea. We looked to compare speed of participants from a four second period centred around when participants spoke the word, with samples of four seconds from outside of word presentation in the dual-task conditions. As a control similar four second samples of time were taken from the climbing alone condition. Sampling was done in the same way for all participants.

Comparing the climbing alone condition speed to the speed in the dual-task conditions at both word and non-word presentation times reveals a significant effect, $F(1.5, 25.69) = 10.62$, $p = 0.002$, $\eta_p^2 = 0.37$. Reverse Helmert contrasts reveal no difference between the climbing alone samples and the non-word samples $F(1,17) = 3.98$, $p = 0.062$ (though this was marginally significant), but a significant difference between these two samples (Climb alone and non-word) combined and the sample taken around word presentation, $F(1,17) =$

12.69, p = 0.002. The implication being that participants had slower speeds around word presentation times compared with the other two sampling conditions, see Figure 5.

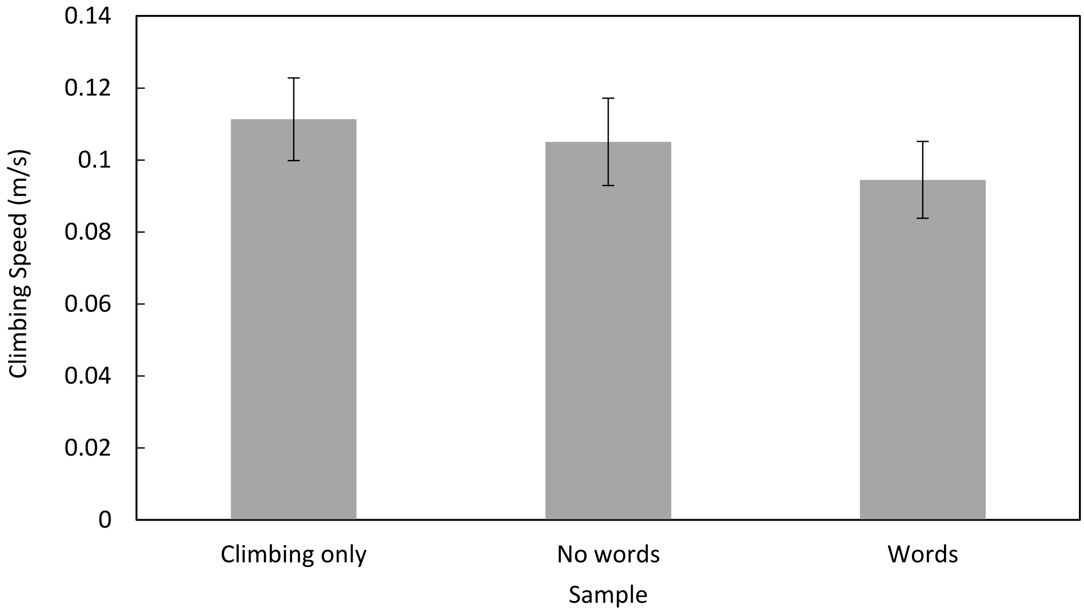

Figure 5. Mean speeds of participants from different sampling conditions. Error bars are standard error.

We further explored this effect with a two by two by four (word/non-word by signal/no signal by time) ANOVA, looking more in-depth at participant speed at each second of the sample. The results reveal significant main effects of time, $F(3, 51) = 4.87$, $p = 0.005$, $\eta_p^2 = 0.22$, with significant linear, $F_{\text{Linear}}(1, 17) = 12.32$, $p = 0.003$, $\eta_p^2 = 0.42$, and quadratic, $F_{\text{Quadratic}}(1, 17) = 5.00$. $p = 0.039$, $\eta_p^2 = 0.23$, trends, indicating a linear or a curve linear decrease over time (Figure 6). Words presentation times against non-word presentation times was also significant, $F(1, 17) = 17.02$, $p = 0.001$, $\eta_p^2 = 0.50$, but there was not a significant effect of signal, $F(1, 17) = 1.38$, $p = 0.26$. Finally, there was a significant interaction effect between time and words, $F(3, 51) = 4.64$, $p = 0.006$, $\eta_p^2 = 0.21$; no other interaction effects were significant (time by sound, $F(3 ,51) = 2.56$, $p = 0.065$; Words by condition, $F(1, 17)$ = 2.568, $p = 0.136$). A significant linear trend for the time by word interaction $F_{\text{Linear}}(1, 17)$ =

9.81, p = 0.006, η_p^2 = 0.37, indicates a divergence between the word and non-word samples across the sample times, Figure 7 displays this relationship, the climbing only condition samples are included as a reference.

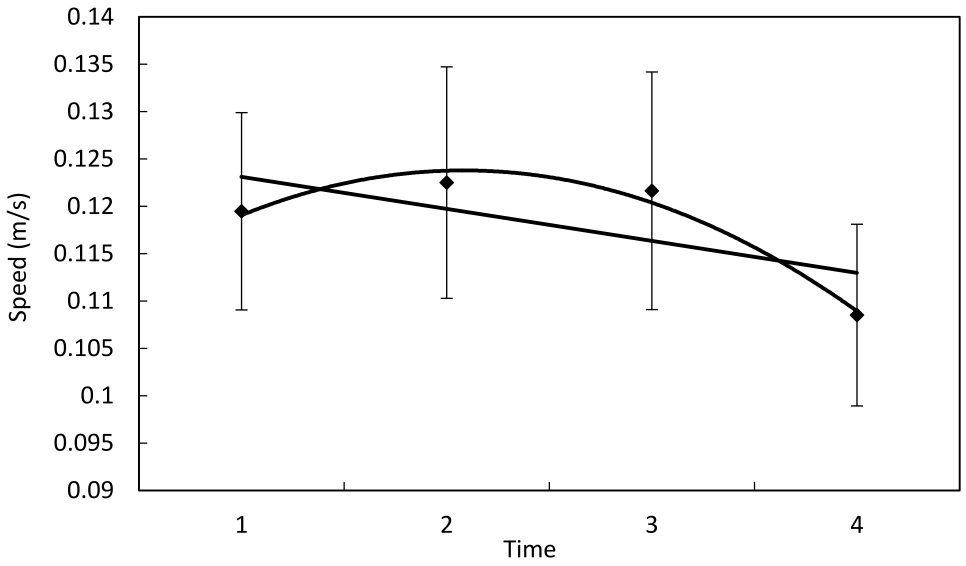

Figure 6. Average participant speed over time, across both dual tasking conditions, error bars are standard error.

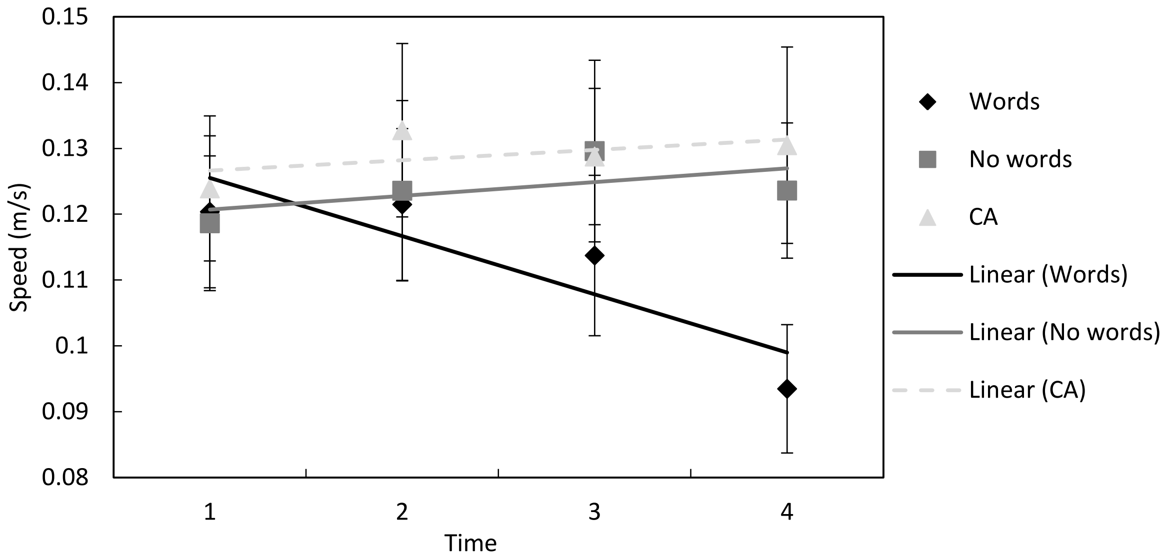

Figure 7. Participant speed at each second across four second sampling period, for word and non-word samples, with the climbing alone average as a comparison, error bars are standard error.

4.5 Graphical Comparisons to Other Research

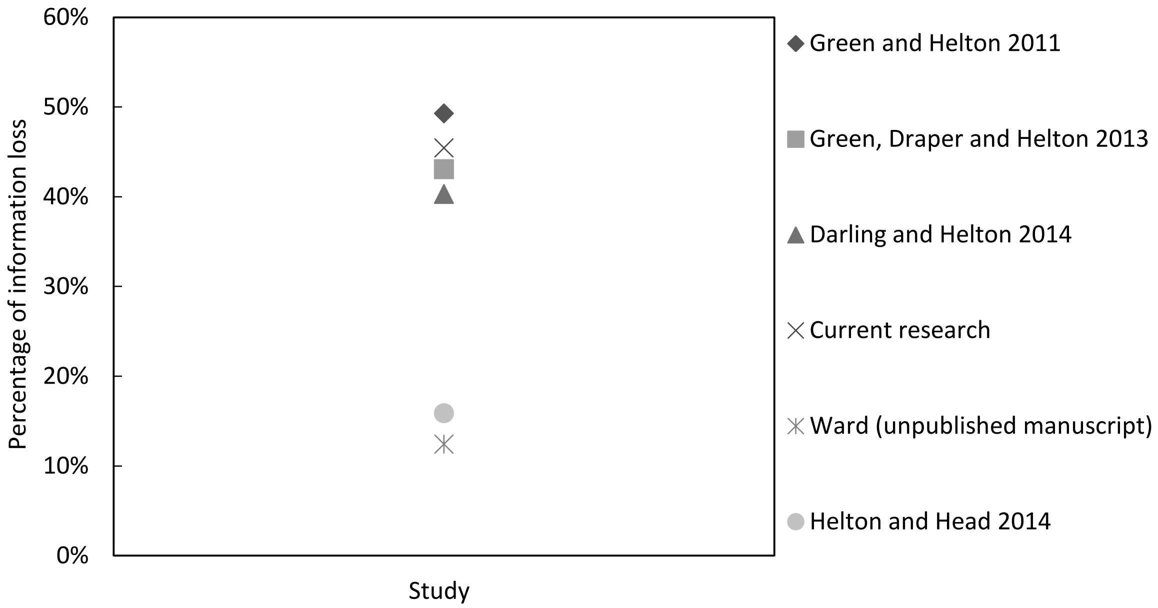

Figure 8. Percentage of information loss in single compared to dual task conditions across studies in word recall tasks.

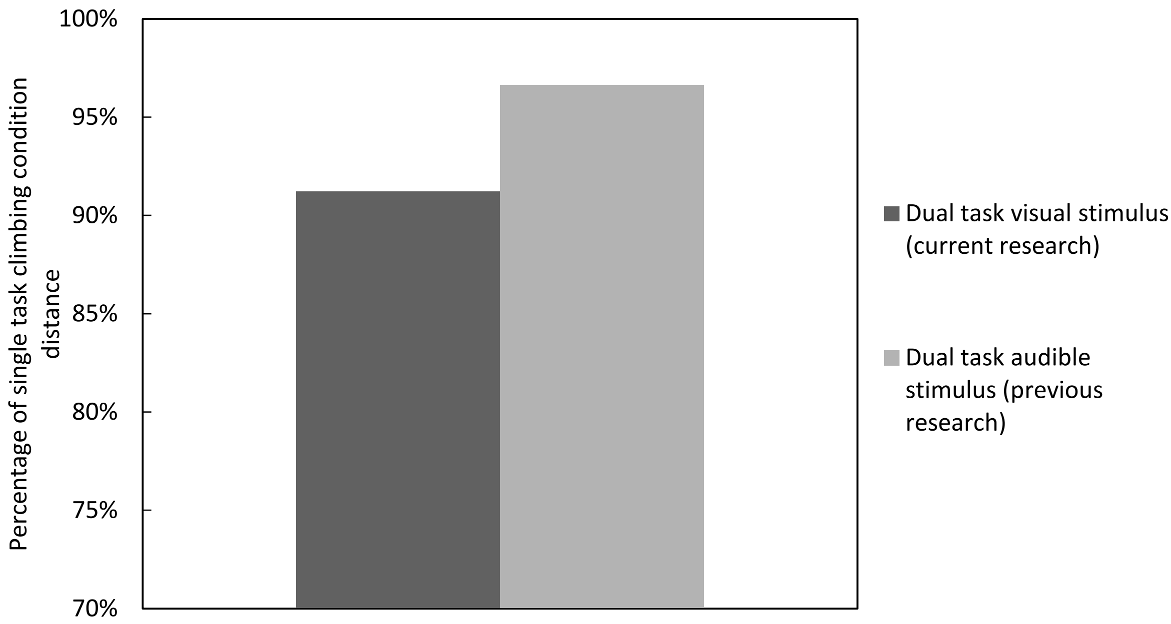

Figure 9. Percentage of the total single task climbing distance completed in the dual task conditions, in the current research compared to previous climbing research by Darling & Helton (2014), Green et al. (2013), and Green & Helton (2011).

5. Discussion

5.1 Findings

The results of our experiment revealed that HMD use (where participants specifically attended to information) in climbing situations results in a decrease in climbing performance. Climbers covered less distance and climbed less efficiently when using the HMD to complete another task. Not only this, but the secondary task suffered as well, indeed more so than the primary task, with participants failing to recall as many words while climbing compared to sitting. In fact, participants recall around 45 percent less information in the dual-task conditions, comparable to the 40 to 50 percent reduction from previous research (Darling & Helton, 2014; Green et al., 2013; Green & Helton, 2011). Further, the use of an auditory warning signal had no mitigating effect on the detriment to climbing performance or word recall when dual-tasking. It did, however, result in participants seeing significantly more words than with no signal when climbing. This audible signal brought the number of words seen up to the level of the seated conditions, but again word recall wasn't improved. This result is interesting as it implies that warning signals in this context can allow people to perceive more information, but not necessarily recall it later. Participants appear to have a limited capacity (around 6 to 8 words) of information they can recall regardless of what information they actually see while climbing. This is likely due to interference at a central memory level rather than a sensory level, with these findings similar to Darling & Helton's (2014).

The self report-scores for both mental demand and fatigue were of mixed congruity with the more objective results. Dual-tasking was more mentally demanding and fatiguing than climbing alone. Comparatively to the seated conditions, however, there was no difference in mental demand or mental fatigue, even though participants recalled less words in the dual-task conditions, although it is possible that the rehearsal of word is generally demanding. The self-report scores for physical demand and fatigue do not coincide well with our other results. Participants did not report climbing dual-tasks as more difficult than the single task climbing condition, even though participants were less efficient and covered less distance in these conditions. They also did not report these conditions as more fatiguing than the single task climbing condition. Concentration did not differ at all across conditions. Task related thoughts appear to increase with the addition of the word tasks. While dual-tasking does not appear to necessitate an increase in on task thinking, but may decrease off task thinking compared to climbing alone. These results suggest that, from the participants' perspective, it is the word task that is most taxing and demanding of their mental faculties.

Motion data used to garner participant speed at a millisecond level allowed us to explore motion around word presentation. This analysis revealed that participants were slower when words were presented, compared to both the climbing only condition, and when words were not presented in the dual-task conditions. Participants appear to slow when reading words which likely impacted on the overall speed of the climbing task, because of the lack of difference between the climbing alone task samples and the non-word presentation samples. Although, the climbing alone samples of speed compared to the dual-task non-word samples of speed was borderline significant, thus perhaps rehearsal of words has a marginal effect on slowing climbing.

Bourdin et al. (1998) found that in two phase movements, probes at the beginning or end of the initial movement inhibited reaction time for the second movement. They postulate that the planning for the second movement occurs at the end of the first rather than a new programming or planning phase. In the context of this experiment if climbers were making a complex movement it would likely encompass more than just two phases. Thus, word presentations at any of these times could affect climbing performance. Similarly, Trafton et al., (2003) and Trafton & Monk (2007) propose a post signal and interruption lag phases model. However, the lack of difference between the two dual-task climbing conditions, imply that these might not account for our results, as participants saw significantly less words with no signal. Further, whether or not the scanning for stimuli may also have played a role in the dual-task conditions is unclear. This is especially pertinent where we would expect less or no stimuli searching in the signal conditions, as the warning was perfectly predictive of the stimuli. Where as, given the pseudorandom nature of the word presentation, scanning might have played more of an important role in slowing climbers in the no signal condition, although dual-task costs are not necessarily affected by temporal unpredictability (Koch et al., 2003), thus it is more likely central memory interference.

Our results align well with other research on dual-tasking finding the consistent result that doing more than one task at a time is detrimental to performance in one or more of those tasks (Bourke et al., 1996; Darling & Helton, 2014; Drugge et al., 2004; Green et al., 2013; Green & Helton, 2011; Head & Helton, 2014; Helton et al., 2013; Nilsson et al., 2005; Strayer & Drews, 2006; C. D. Wickens, 1976, 2002, 2008; Witt, 2007; Yogev-Seligmann et al., 2010). More specifically, we found similar results to past research on climbing and post task word recall (Darling & Helton, 2014; Green et al., 2013; Green & Helton, 2011) with a 45 percent decrease in word recall, similar to the 40 to 50 percent found previously. Thus, modality of the secondary task does not appear to influence the detriment to word recall, however relative to other dual-task word recall studies the detriment to word recall appears greater with the complex physical activity of climbing. Both Ward (unpublished manuscript) and Head & Helton (2014) found less of a detriment to word recall in seated computer tasks, around 12 to 16 percent loss of information (Figure 8 in the results). We also compared change in distance covered in the dual-task climbing conditions, to single task climbing conditions across the previous climbing research. This revealed that the type of stimuli presentation appears to make some difference. Climbers, presented with audible stimuli, traversed approximately 97 percent of the distance they covered in the single task climbing condition; while with visual stimuli presentation, participants traversed around 91 percent of the distance they covered in the single task climbing condition. This information is displayed in the results in Figure 9. This has a particularly important implication; using HMDs in climbing (and likely other complex physical tasks) is not only detrimental to performance in information recall and primary task performance, it is also likely more detrimental to later recall than seated tasks. Perhaps the lack of inherent risk of the primary task (falling) was influential in these differences. Given the risks associated with falling during climbing, participants likely allocate more, or even over allocate, resource to maintaining climbing performance. Though it is more likely that the high attention needed to maintain climbing performance (Draper et al., 2008, 2010; Helton et al., 2013), impaired word rehearsal. Generally the findings of these comparisons (a larger impact on climbing performance with visual stimuli than audible stimuli and larger impact on later recall with climbing) are in line with multiple resource theory.

5.2 Theoretical Implications

At a basic level these results reveal that participants can only attend to small amounts of information when performing a climb and this may generalise to other complex physical tasks. They can be assisted to see more information but do not necessarily remember this additional information. Further physical primary tasks may impact more severely on information recall than less physical tasks. Taking into account this research and previous research there appears to be some continuum of dual-tasking interference.

Even though exercise can improve speed of visual search (McMorris & Graydon, 1997), participants still appear to perform worse in visual compared to audio conditions, and much worse than in a seated visual task, manual tracking or target selection (Head & Helton, 2014; Ward, unpublished manuscript). Taken together, these results imply that the majority of interference is not likely at a visual search level, but rather a central memory level. Considering the words seen to words recalled ratio, in this work and Darling & Helton's (2014), where participants see the majority of the words but do not necessarily recall them, this implication is more clear.

When dual-tasking it appears to make little difference if the stimuli are audible or visual in terms of later information recall; this makes sense as the information is likely stored centrally in the same format (semantically). Although, audible warning systems can help facilitate information viewing, later recall remains at similar levels to no warning conditions. Interruptions could be the cause of slowing in the warning condition, whereas in the non-warning condition scanning interference should be the cause as participants did not see a lot of the words. This may be unlikely given the lack of difference between our dual-task conditions. Again, this would seem to point to central processing interference, rather than perceptual interference, as the impact of climbing on later information—word—recall.

Finally, the comparison to the previous studies reveals that climbers covered less distance with visual words than audible ones. If this is a replicable result, then it may be that climbers slow down more for visual words than audible ones. This type of result would be in line with multiple resource theory, where similar stimuli input should cause more interference (Wickens, 1976, 2002, 2008).

5.3 Practical Implications

As new technologies are adopted into work environments concerns arise around their impact on performance. When a firefighter is receiving information about floor plans, GPS, biometric data, and environmental data on a HMD, they will likely forget much of that information and have some decrement to their performance in searching the building, particularly if they are continually attending to the information. For search and rescue, descending and ascending cliff faces, entering or descending into buildings is hazardous, and communication with team members, though important, could have negative effects on performance. Information about floor plans or what victims look like, last known locations, weather phenomenon, and other relevant information for a search and rescue operation could all be provided via HMD, though it likely comes at a cost to performance.

The literature indicates the detrimental consequences of dual-tasking, and practically this research suggests that using audible over visual stimuli might have a small effect in mitigating the decrement to performance, though this would need further investigation. Secondly, having an audible warning prior to stimuli presentation does not appear to diminish the dual-task decrement (if anything, it makes participants slower); it can, however, facilitate information viewing, or initial awareness. Thus, if an operator needed information that they were not necessarily required to remember, presentation with an audible warning would be appropriate. This would be especially useful in a situation where the device has self facilitated memory recall (the device acts as external memory).

The development of adaptive computer systems is probably still a way off, but it could be monumentally helpful in hazardous environments. Having a system 'remember' information for you, and be able to present it at appropriate times and ways, deployed in a light weight non-invasive package, would be the ultimate objective. Prior to that, simply storing information received and allowing a user to access that information easily when needed, likely by voice commands (He et al., 2014; Witt, 2007), could make a difference to the decrement in dual-tasking performance.

Wearable computers and HMDs have the potential to provide users with improved situational awareness. Hence, the application to military, search and rescue, firefighting, police, medical, and other areas. Even with a system that stores information for you, or one with excellent adaptive feedback, investigating the implications would be necessary. Exploring whether these systems still induce performance decrements is important, along with understanding compliance and reliance factors involved in them. For example, in a search and rescue context, over-reliance on a search aid device might result in not completing search processes properly, hence a victim might be missed. Alternately, information on changes in weather, or chances of slips and avalanches provided by an adaptive system might be ignored, risking the safety of a search and rescue operator. Given the current limitation of these systems, devices would need to present less information at a time, and attempt to do so when the user is not performing another task. This would likely be the case in most complex physical activities or hazardous jobs.

5.4 Limitations of the Research

Firstly, the climbing location used was perhaps not comparable enough to a natural face or the kind of climb you might face when entering a building. However, the skills necessary to climb an indoor wall are still applicable to a natural surface. Further, the use of this wall made it possible to compare to previous climbing research. Although the number of words used was 19 not 20, thus comparing the word recall to previous research may have been problematic. Participants were also aware that words would show up on the display, where as in a real world context they might not know what type of information to expect. Still, there would certainly be some information presented that they would know was coming. The safety of the low height and the bouldering mat could have influenced the way climbers performed; results might differ with a top roped climb or a lead climb, though this could be more difficult to control. Top rope or lead climbing could induce more fear (Draper et al., 2008, 2010) which can affect climbing performance (Green et al., 2013).

There was a difference in speed measurements between the manual calculations and Kinovea, as well as a difference in speed between times taken over 4 seconds and those taken over single seconds, however, the relationships between conditions was found to be similar to the manual calculation, except faster. There are question around how well the secondary task simulated the types of secondary task search and rescue responders might do. Perhaps something more akin to the simulated communication task that Darling & Helton (2014) used would be more appropriate. Additionally, the sample used was quite young and might not represent the types of people who do jobs such as search and rescues, firefighting, or military police work. Finally, the sample size was quite small due to the difficulty of finding climbers willing to complete the experiment, though it was comparable to other research (Darling & Helton, 2014; Green et al., 2013; Green & Helton, 2011)

5.5 Future Research

Future research should look more in detail at the effect different stimuli modalities have on performance. Further, it would be interesting to investigating the visual scanning climbers undertake when performing a secondary task. Using eye tracking technology it would be possible to see how much searching for the secondary task stimuli participants do, with and without an audible signal. Other complex physical activities might also want to be addressed in future research to see if these differ in performance decrement compared to climbing; top roped or lead climbing might also warrant investigation. This type of climbing might be more parallel to a typical search and rescue operation climb, though likely harder to control for variables (such as the belayer). Additionally, looking at physiological measures while climbing (which could indicate stress) could show biological responses high attention and cognitive demands.

There is cause to understand how the information seen relates to the information remembered. Where in this study participants saw more information with an audible signal they recalled the same as in a dual-task condition, which raises questions around how the way the information is presented can affect performance. For example, given Bourdin et al.'s (1998) model of interruption in planning, would giving participants words to remember before the traverse still affect climbing performance, or affect it to the same degree?

Additionally, the modality of response would be an interesting area for additional work, looking at how speech vs. manual/gesture input affects the dual-tasking decrement. Finally, examining the impact that adaptive feedback systems or information storage systems have on performance and HMD use, would be of high value. This research would be important in the design and development of these systems, hopefully improving them.

5.6 Conclusion

With the application of HMDs and other wearable computers to firefighting, surgery, search and rescue work, and other areas, there is an increasing need to understand the costs of these technologies. This research shows that there are deleterious effects for both the amount of information one can recall and primary task performance when using a wearable computer. Additionally, it reveals that climbers slow down during information—word—presentation, while also suggesting that visual stimuli are worse for climbing performance than audible stimuli. These types of results should be helpful in adapting wearable computer use to hazardous environments, and when designing wearable systems. The general findings of this research, and the pervious climbing research, should be valuable to search and rescue workers, firefighters, and likely for surgeons and military or police personnel as well.

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Appendix A

Word Lists

List 1	List 2	List 3	List 4
slipper	candy	fabric	costume
glacier	reptile	mucus	saloon
pepper	comrade	hurdle	kerchief
settler	sunset	leopard	python
odour	shotgun	pianist	fiord
dreamer	profile	footwear	bullet
cigar	scarlet	cuisine	mammal
captive	harness	hammer	salad
banner	bandit	trellis	lemon
poster	portrait	garments	twilight
arrow	barrel	nectar	abode
piston	sunburn	sultan	jelly
pencil	warbler	trumpet	singer
hardwood	lobster	doorman	goblet
beggar	rubble	hillside	painter
invoice	bouquet	pudding	wigwam
robber	hostage	kettle	typhoon
elbow	cellar	daybreak	basement
butcher	tweezers	speaker	sulphur
salute	abyss	portal	juggler

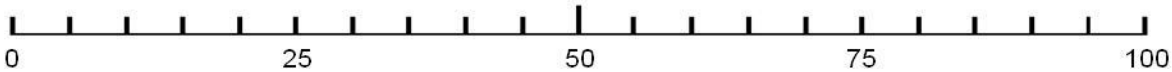
Appendix B

Self Report Questionnaire

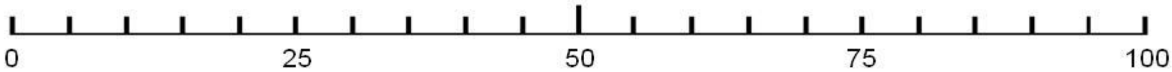
MALE or FEMALE (circle one) Age: ______ ID_______ Condition/List_______

For the following items use the response scale below the item by circling the vertical line closest to your answer; the scale goes from 0 (**very low**) to 100 (**very high**). These questions refer to you experience during the task.

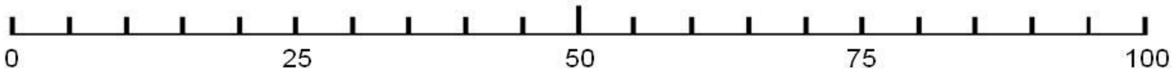
1. **Mental Demand** - How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)?



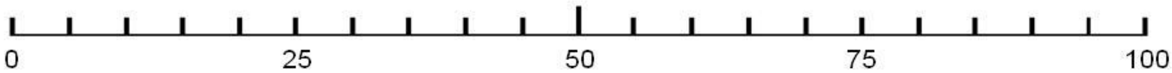
2. **Physical Demand** - How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)?



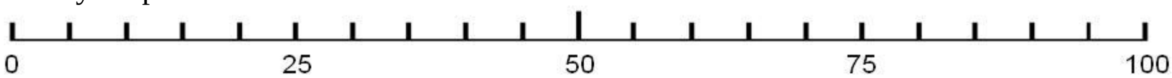
3. **Temporal Demand** - How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred?



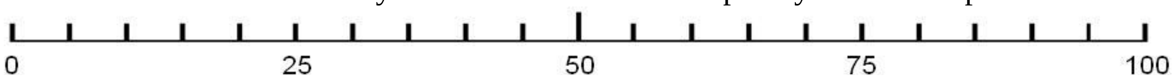
4. **Emotional Demand** – How emotionally demanding was the task?



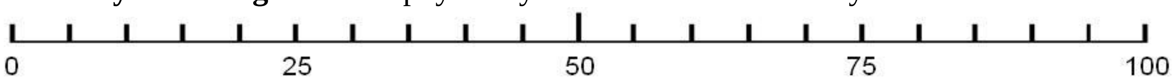
5. **Performance Monitoring Demand** – How much did the task require you to monitor your performance?



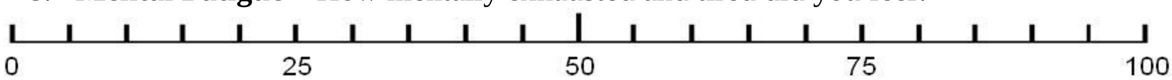
6. **Effort** – How hard did you have to work to accomplish your level of performance?



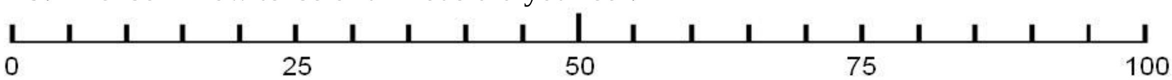
7. **Physical Fatigue** – How physically exhausted and tired did you feel?



8. **Mental Fatigue** – How mentally exhausted and tired did you feel?



9. **Tense** – How tense or anxious did you feel?



10. **Unhappy** – How unhappy did you feel?

0 25 50 75 100

11. **Motivation** – How motivated were you to do well?

0 25 50 75 100

12. **Task Interest** – How interesting was the task?

0 25 50 75 100

13. **Self Related Thoughts** - How much did you think about yourself?

0 25 50 75 100

14. **Concentration** – How focused on the task were you?

0 25 50 75 100

15. **Confidence** – How confident were you during the task?

0 25 50 75 100

16. **Task Related Thoughts -** How much did you think about the task?

0 25 50 75 100

17. **Task Unrelated Thoughts** – How much did you think about something other than the task?

0 25 50 75 100

Appendix C

Information Sheet and Consent Form.

UNIVERSITY OF CANTERBURY
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[Date]

The use of HMDs in high angle climbing
Information Sheet for Participants

I am a Masters student at the University of Canterbury and this research fulfils the thesis requirement for that degree. The research looks at the use of Head Mounted Displays (HMD) while rock climbing. The focus is on the effects of dual tasking while rock climbing.

This study consists of 5 tasks, two seated word recall tasks and three rock climbing tasks. Of the three rock climbing tasks two will have a word recall task as well. As a participant you will be asked to complete all 5 of these conditions. You are free to warm up and familiarise yourself with the climbing wall prior to the commencement of the tasks. After each task you will be asked to write down as many words as you can remember from each task, then fill out a questionnaire on your thoughts and emotions during the task. There will be a rest period of 2-5minutes between tasks (longer if needed).

During the rest period another task will be completed. In this task you will be shown shapes on a computer. After the presentation of each shape another two shapes will appear and you will be asked to select the one you think is most like the original shape.

During the three climbing conditions you will be filmed, however, the camera will only record your back and not capture your face. This film will only be used to code climbing performance and will be transferred to a password protected computer that is kept in a lockable office before being erased from the camera. Questionnaires will not require personal information, sensitive information or contain identifying questions. The whole experiment should take around 45 minutes to complete and you will be compensated for your time.

In the performance of the tasks and application of the procedures there are risks of falling off the climbing wall. To minimise this risk or the risk of injury a heavily padded mat is present below the wall where you will climb and you will be climbing below 3.3m which is the designated safe height for non-roped climbing. Further if you feel unsafe at any time during the task you can simply step off the climbing wall to the safety of the mat.

Participation is voluntary and you have the right to withdraw at any stage without penalty. If you withdraw, I will remove information relating to you provided you can supply your participant number.

The results of the project may be published, but you may be assured of the complete confidentiality of data gathered in this investigation: your identity will not be made public without your prior consent. To ensure anonymity and confidentiality, no names or identifiable information will be acquired on the questionnaires and videos will be transferred to a password secured computer and deleted from the camera. This computer will be kept in a lockable office to ensure it can be accessed only by the researchers. All information relating to this research will be destroyed after a 5 year period. A thesis is a public document and will be available through the UC Library.

You may receive a copy of the project results by contacting the researcher at the conclusion of the project.

The project is being carried out as a requirement for the completion of the applied psychology masters program by Alex Woodham under the supervision of Dr William (Deak) Helton and Dr Mark Billinghurst, who can be contacted at deak.helton@canterbury.ac.nz and mark.billinghurst@canterbury.ac.nz respectively. They will be pleased to discuss any concerns you may have about participation in the project.

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee, and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz), using the reference HEC2014/31/LR.

If you agree to participate in the study, you are asked to complete the consent form and return it to the researcher before commencing the experiment.

Regards
Alex Woodham

Department of Psychology
Telephone: +64 022 171 4924
Email: alex.woodham@pg.canterbury.ac.nz

The use of HMDs in high angle climbing
Consent Form for Participants

I have been given a full explanation of this project and have had the opportunity to ask questions.

I understand what is required of me if I agree to take part in the research.

I understand that participation is voluntary and I may withdraw at any time without penalty. Withdrawal of participation will also include the withdrawal of any information I have provided should this remain practically achievable.

I understand that any information or opinions I provide will be kept confidential to the researcher and that any published or reported results will not identify the participants. I understand that a thesis is a public document and will be available through the UC Library.

I understand that all data collected for the study will be kept in locked and secure facilities and/or in password protected electronic form and will be destroyed after Five years.

I understand the risks associated with taking part and how they will be managed.

I understand that I am able to receive a report on the findings of the study by contacting the researcher at the conclusion of the project.

I understand that I can contact the researcher Alex Woodham (alex.woodham@pg.canterbury.ac.nz) or supervisor Dr William Helton (deak.helton@canterbury.ac.nz) for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

By signing below, I agree to participate in this research project.

Name:

Date:

Signature:

Alex Woodham